Calculating the Power Demand in Turning of AISI 316L Stainless Steel Through the Cutting Forces Data

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***Abstract*—Austenitic stainless steel AISI 316L has been widely used for orthopedic implants due to its mechanical properties, corrosion resistance and biocompatibility. Machining of austenitic stainless steel are often regarded as 'difficult to machine' and classed a single group of steels, based on experience with the most common austenitic types. This paper presents a methodology for practical calculation of power demand based on cutting force that will be compared with experimental results especially turning process. Based on a previously proposed definition, the power demand in metal cutting is the energy required cutting. This paper provides a complete list of mathematical expressions needed for the calculation of power demand and demonstrates their utility for turning operation of austenitic stainless steel using coated and uncoated carbide.**

Keywords*—*cutting force; power Demand; turning; stainless steel

I. Introduction

The manufacturing sector is a key industry that relies on the use of energy in driving value addition through manufacturing processes. Machining is widely used in most manufacturing industries hence represents a major portion for energy demand. Reducing the energy demand of machine tools can significantly improve the environmental performance of manufacturing processes and systems. Furthermore, given that machining processes are used in manufacturing of many consumer products, improving the energy efficiency of machining-based manufacturing systems could yield great deal of reduction in the environmental impact of consumer products. Yet, despite decades of optimizing the machining processes based on cost and productivity, optimizing their energy use had not received significant attention.

The first step toward reducing energy demand in machining is to calculate and evaluate the power demand based on experimental data. The followings are some of the literatures on the power demand calculation during machining of various workpiece materials. The investigation of Bhattacharya et al. [1] outlines an experimental study to investigate the effects of cutting parameters on power demand by employing Taguchi techniques during high speed machining of AISI 1045 using coated carbide tools. It was reported that significant effect of cutting speed on the surface roughness and power demand, while the other parameters did not substantially affect the responses. The report by Hanafi et al. [2] outlines the effect of cutting parameters on power demand when turning poly ether ether keytone reinforced with 30% of carbon fibers using TiN coated tools under dry conditions. The obtained results have indicated that cutting speed and depth of cut are the most influential parameters. Fratila and Caizar [3] reported the effect of cutting parameters in face milling when machining AlMg3 (EN AW 5754) with HSS (high speed steel) tool under semi-finishing conditions to the power demand. These literatures reported direct power demand measurement during the experiments. The works used statistical analysis towards determining the cutting parameters setting in order to achieve the preferred machining responses, including minimum power demand.

The above literature reviews show that so far no efforts have been made toward calculation power demand based on data of cutting force and comparing with experimental results of power demand during machining of AISI 316L austenitic stainless steel. AISI 316L austenitic stainless steel are increasingly being used in manufacturing especially in medical and aerospace industries. However, it poses a difficult machining problem due to its material properties. In the present work, an attempt has been made to calculate the power demand in turning of austenitic stainless steel by using the data of cutting force.

II. Calculation of Power Demand

A. Cutting Forces

Turning is a very important machining process in which a single point cutting tool removes unwanted material from the surface of a rotating cylindrical work piece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried on lathe that provides the power to turn the work piece at a given rotational speed and feed to the cutting tool at specified rate and depth of cut. Therefore three cutting parameters namely cutting speed, feed rate and depth of cut need to be optimized in a turning operation. Turning operation is one of the most important operations used for machine elements construction in manufacturing industries i.e. aerospace, automotive and shipping.

Turning produces three cutting force components as shown in Figure1, (the main cutting force i.e. thrust force, (F_Z), which acts in the cutting speed direction, feed force, (F_X), which acts in the feed rate direction and the radial force, (F_Y), which acts in radial direction and which is normal to the cutting speed). Out of three force components the cutting force (main force) constitutes about 70% to 80% of the total force 'F' and is used to calculate the power '*P*' required to perform the machining operation [4-5]. The cutting forces generated in metal cutting have a direct influence on generation heat, tool wear or failure, quality of machined surface and accuracy of the workpiece.

Cutting power is the product of main cutting force and the cutting velocity and is a better criterion for design and selection of any machine tools. Power demand may be used for monitoring the tool conditions. The equation for the power is:

$$P_c = F_c * V_c \quad (1)$$

where P_c is the power of cutting process in Watt, V_c is the cutting speed in m/min and F_c is the main cutting force in N.

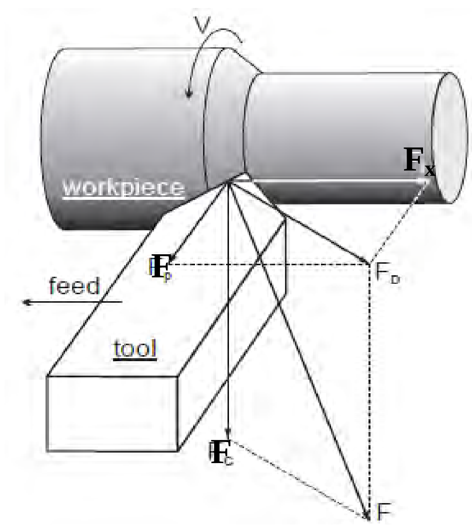


Figure 1. Cutting force components during metal cutting in turning

The power is dissipated mainly in the shear zone (due to the energy required to shear the material) and on the rake face of the tool (due to tool-chip interface friction). The sharpness of the tool tip also influences forces and power. Because it rubs against the machined surface and makes the deformation zone ahead of the tool larger the worn out tools require higher forces and power.

B. Power Demand in Turning Process

Most studies provided in literature focus on measuring the power demand of different types of machine tools as a basis for identifying optimization potentials. A commonly accepted energy breakdown by [6] divides the power demand of machine tools into three different modes: idle mode, run-time mode, and production mode. In idle mode, the machine is ready for production and components such as the operation panel and fans accumulate to the constant power demand. During run-time mode, further auxiliaries are activated, which, once turned on, have a constant power demand (e.g. spindle motor and coolant pumps).

The production mode represents the power demand while removing material. This portion is variable and dependent on the load applied to the machine. Numerous studies showed that the power necessary for removing the actual material has only little impact on the overall energy demand [7-8]. Thus, different approaches aimed to reduce the constant part by either improving specific components or by reducing the overall cycle time [9-10]. Influences on power demand were identified, such as process parameters [11], selection of tooling [12], and workpiece material [13]. Hence, power measurements are highly dependent on a variety of preconditions that directly affect the obtained data and therefore require standardized test procedures.

Total power (P) used in lathe operations can be evaluated from the power consumed by the machine during the setup operation (P_0), and during the cutting operation (P_c). It can be calculated by the product of machining time and power consumption in unit time, as modeled by [7] in equation (2).

$$P = P_0 + k.\dot{} \tag{2}$$

where P_0 is the power [W] consumed by all machine modules for a machine operating at zero load (machine is not cutting), k is specific cutting energy [Ws/mm^3], and $\dot{}$ is material removal rate [mm^3/s]. Specific energy value of k can be referring to [14].

The total power consumption in cutting process could be modified from the equation modeled by [15]:

$$P = P_0 + P_c \tag{3}$$

where P_c is the power of cutting operation and V_c is cutting speed (m/min). A typical relationship between cutting force components acting on the cutting tool in a 3D single point cut is defined by Equation as follow [18]:

$$F_c = \sqrt{\quad + \quad + \quad} \tag{4}$$

where F_c was resultant of cutting force, F_X was radial force, F_Y was feed force, and F_Z was cutting force. Thus, the equation of cutting process is:

$$P = P_o + (\sqrt{\quad + \quad + \quad})\, V_c \tag{5}$$

III. Experimental Design

A. Materials and Cutting Tools

Turning process carried out on a 5.5kW two-axes CNC lathe machine with cutting speed (V_c) of 90 to 210 m/min, feed rate of 0.1 to 0.22 mm/rev, and 0.4 mm for depth of cut (constant). The process was performed with dry turning. A Kistler force dynamometer model 9265B was used to record cutting force during experimental turning operations. Model 5019 Kistler multi channel amplifiers were used to convert the dynamometer output signal into a voltage signal appropriate for the data acquisition system. The input sensitivities of the charge amplifier were set corresponding to the output sensitivity of the force dynamometer in the direction of the forces.

The workpiece material was an austenitic stainless steel AISI 316L which has a composition of 0.03% C, 0.75% Si, 2.0% Mn, 18.0% Cr, 0.03% S, 0.045% P, 14.0 Ni, 0.10% N, and balance Fe.

The cutting tool used for the experiment were an advanced CVD nano-texture TiCN coating carbide with nano-texture Al_2O_3 (MC7025) and uncoated (UTi20T) that designated as ISO CNMG 120408.

B. Experimental Setup

The turning experiments were carried out on a 2-Axis CNC lathe machine "ALPHA 1350S". In order to develop the power consumption model for this machine, power measurements were performed under various cutting parameter settings. Three portable power monitor (OMRON ZN-CTX21) were used within the turning experiments including three clamp meter (OMRON ZN-CTM11). One device was applied for measuring the main power, while the others were used for the measurement of the process power including the spindle and axis drives. The constant power can be derived by deducing the process power from the total power. The measured data was acquired and visualized through the software "Wave Inspire ES". The power measurement setup is demonstrated in Figure 2.

Figure 2. Power measurement setup

IV. Results and Discussion

A. Cutting Forces

Cutting force generated during turning process that started the cutting tool to touch the workpiece until the completion of cutting process and it can be measured by a dynometer connected with a system interface and the measurement results were shown as in Figure 3.

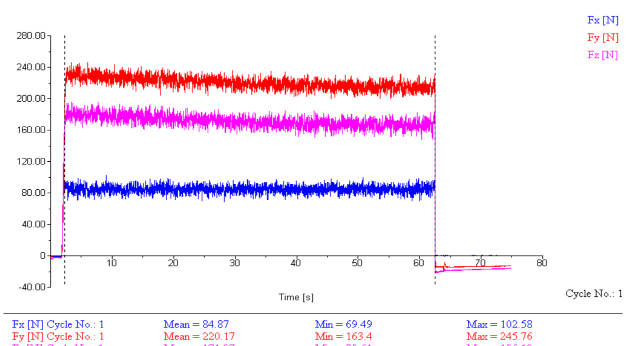


Figure 3. Graph of cutting force

The results of cutting force data for coated and uncoated carbide was shown in Figure 4 below is made in the form of a graph of cutting force with feed rate for each of the different cutting speed. The high of cutting force (312.07 N) was obtained from the selection of cutting speed and feed rate is high, while the lower cutting force (154.86 N) was obtained from the selection of cutting speed and feed rate are low.

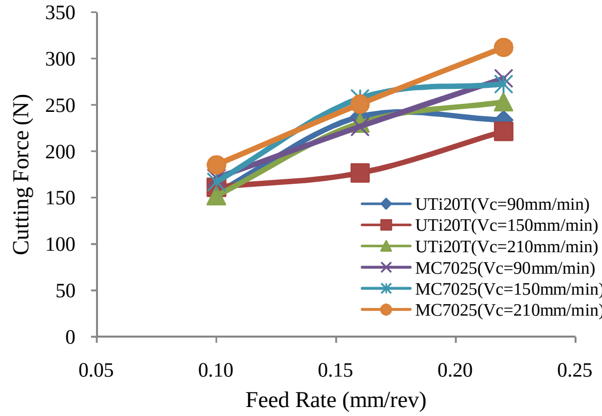


Figure 4. Graph for results of cutting force

B. Power Consumption

Table 2 and 3 presents results for experimental data generated during turning of austenitic stainless steel work piece. This result shows that cutting speed has the most significant effect on the power consumption, followed by feed rate. The lowest power is obtained when all the factors value at their minimum value.

Table 2. Result of power consumption for MC7025 coated carbide

No.	*Vc* (mm/min)	*f* (mm/rev)	*Pc* (kW)		*Error*
			Experiment	*Equation*	
1	90	0.10	0.870	0.855	0.011
2	150	0.10	1.062	0.993	0.049
3	210	0.10	1.363	1.273	0.064
4	90	0.16	0.920	0.952	0.022
5	150	0.16	1.234	1.257	0.016
6	210	0.16	1.494	1.492	0.001
7	90	0.22	0.991	1.039	0.034
8	150	0.22	1.238	1.266	0.020
9	210	0.22	1.598	1.665	0.048

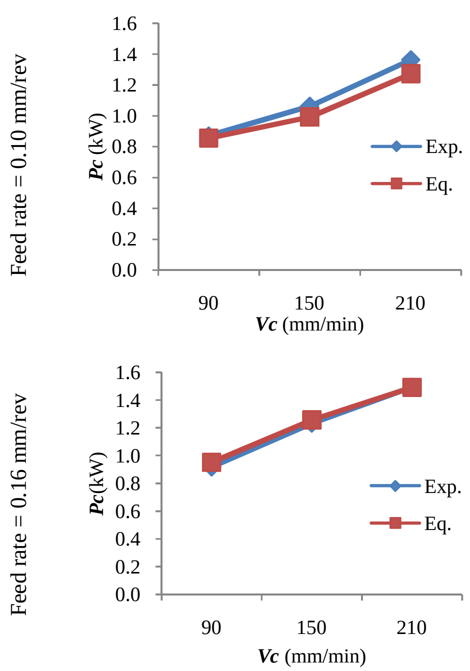
Table 3 Result of power consumption for UTi20T uncoated carbide

No.	*Vc* (mm/min)	*f* (mm/rev)	*Pc* (kW)		*Error*
			Experiment	*Equation*	
1	90	0.10	0.636	0.699	0.045
2	150	0.10	0.908	1.009	0.072
3	210	0.10	1.160	1.145	0.010
4	90	0.16	0.730	0.830	0.070
5	150	0.16	1.020	1.089	0.049
6	210	0.16	1.423	1.420	0.003
7	90	0.22	0.610	0.721	0.079
8	150	0.22	1.027	1.117	0.064
9	210	0.22	1.524	1.508	0.011

Based on tables 2 and 3 above, hence made a form of graph *Pc* with cutting speed and for different of feed rate and cutting tool. This chart was also made to determine the differences in power consumption derived from experimental results and calculation results that using Eq. 6 above.

C. Discussions

The experiment results obtained cutting force as shown in Figure 4, where cutting force will increase for increasing the cutting speed and feed. This phenomenon was confirmed by research carried out by [19] observed that the selecting of a cutting speed and feed rate from the charts that depends on cutting force model for turning Hastelloy C-276 utilizing response surface methodology. It concluded that the effect of feed rate on cutting force is much more evident than the effect of speed and the cutting force slightly affected by cutting speed, whilst it increases when the feed or depth of cut is increased. The same case that has been investigated by [20] who concluded that generally the three forces (radial, tangential, and feed force) increased when feed rate was Increased and the cutting speed were found to be similar when the feed rate was Increased.



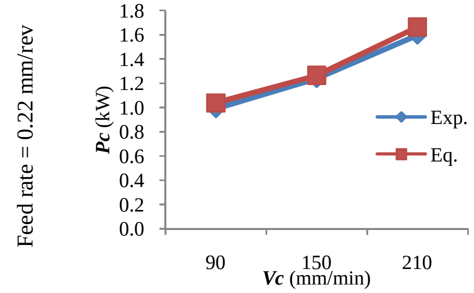


Figure 5. Power consumption at variety of feed rate for MC7025

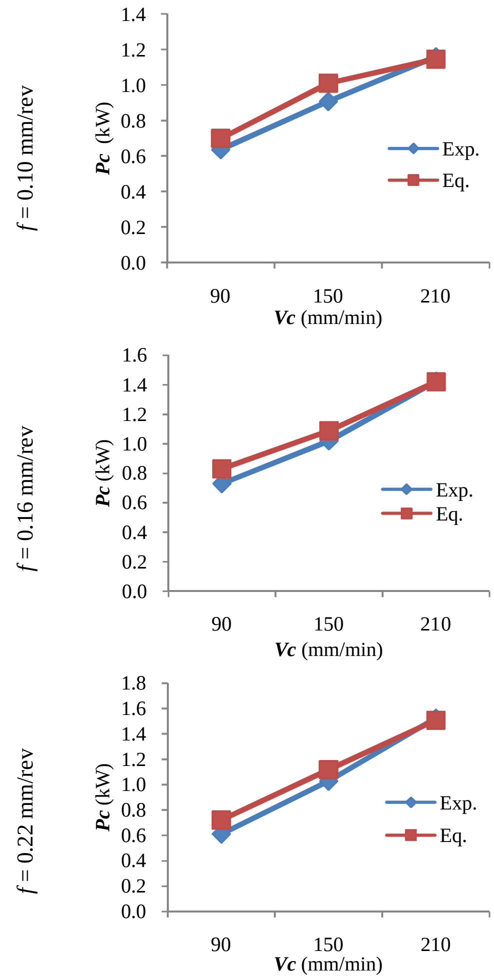


Figure 6. Power consumption at variety of feed rate for UTi20T

For a description the power consumption, can be expressed that power consumption is minimum at the low level of cutting speed as proved in the Figure 5. The figure shows the main effect plot for power consumption showing the effect of cutting speed, and feed rate. The results explain that decreasing cutting speed and feed rate, there is continuous decrease in power consumption i.e. smaller values of cutting parameters and larger values of cutting parameters there is required larger power for machining austenitic stainless steel. This result is consistent with the findings conducted by [21] summarized that decreasing cutting speed, feed rate, depth of cut and tool nose radius, there is continuous decrease in power consumption i.e. smaller values of cutting parameters and tool nose radius produces smaller power consumption and larger values of cutting parameters there is required larger power for machining EN-31 steel. As well as [22] observe the effect of cutting parameter and cutting environment in turning of AISI P-20 tool steel, it is clear that lowest power consumption is at lowest level of cutting speed, feed, depth of cut and nose radius.

Besides, if we consider Tables 2 & 3 and Figures 5 & 6, it can be seen that the power consumption was obtained from the experimental results and calculation results show the percentage of similarity is not too big. The percentage error range between the experimental and calculation value for P_c is 0.1 to 7.9%. It can be said that the calculation model developed were reasonably accurate for both of MC7025 coated carbide and UTi20T uncoated carbide.

V. Conclusion

In this paper, AISI 316L austenitic stainless steel have been dry-machined in a two-axes CNC lathe machine and a Kistler force dynamometer model 9265B was used to measure the cutting force values of work pieces. The important conclusions were taken from this study are as follow:

1. Considering the individual conditions, cutting speed was more influencing factor to cutting force and power consumption, followed by feed rate.
2. As the spindle speed increases, for lower feed rates, the surface roughness decreases, for higher feed rates, the surface roughness changes considerably.
3. The increase in feed rate causes the surface roughness to increase and then decrease. For lower depth of cut, as the feed rate increases, surface roughness decreases and then increases.
4. The cutting force and power consumption have a direct relationship to influence each other, in other words cutting force was increase as well as power consumption increases.
5. The similarity of power consumption based on experiments and calculation have a percentage errors between 0.1 to 7.9%, it means that calculation of power consumption based on data of cutting force can be used and considered for other experiments.

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